The Energy Balance at the Base of the Solar Transition Region

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The hydrogen Lyman alpha line is formed at the base of the chromosphere-corona transition region, at temperatures mostly above 10000K. Models of the transition region based on a balance between classical thermal conduction of energy downward from the corona and radiative energy losses predict a temperature gradient at the base of the transition region that is much too steep to produce the Lyman-alpha emission that is observed. Empirical models, on the other hand, have included a 20000K temperature plateau to account for the observed Lyman-alpha and Lyman-beta line profiles.

We show here that the heat flow downward from the corona is grossly underestimated by the Spitzer thermal conductivity formula in the Lyman-alpha forming region, and that if the proper transport theory is considered, the heat flux can be great enough to account for the observed Lyman-alpha intensity.

Our calculations of the heat flux include three components: the conductive heat transport (or translational conductivity, according to Devoto 1968), the internal energy diffusion (or reactive conductivity), and the kinetic energy diffusion. Figure 1 shows the calculated total heat-flux thermal coefficient from one of our model calculations. Included for comparison are results from the Spitzer formula and from the equations derived by Nowak and Ulmschneider (1977). The Spitzer result assumes that the plasma is fully ionized, which is not the case in the Lyman-alpha forming region. Nowak and Ulmschneider did not include a consistent solution of the ambipolar diffusion equations. Ambipolar diffusion is most important at intermediate ionization where the Lyman alpha line is formed.

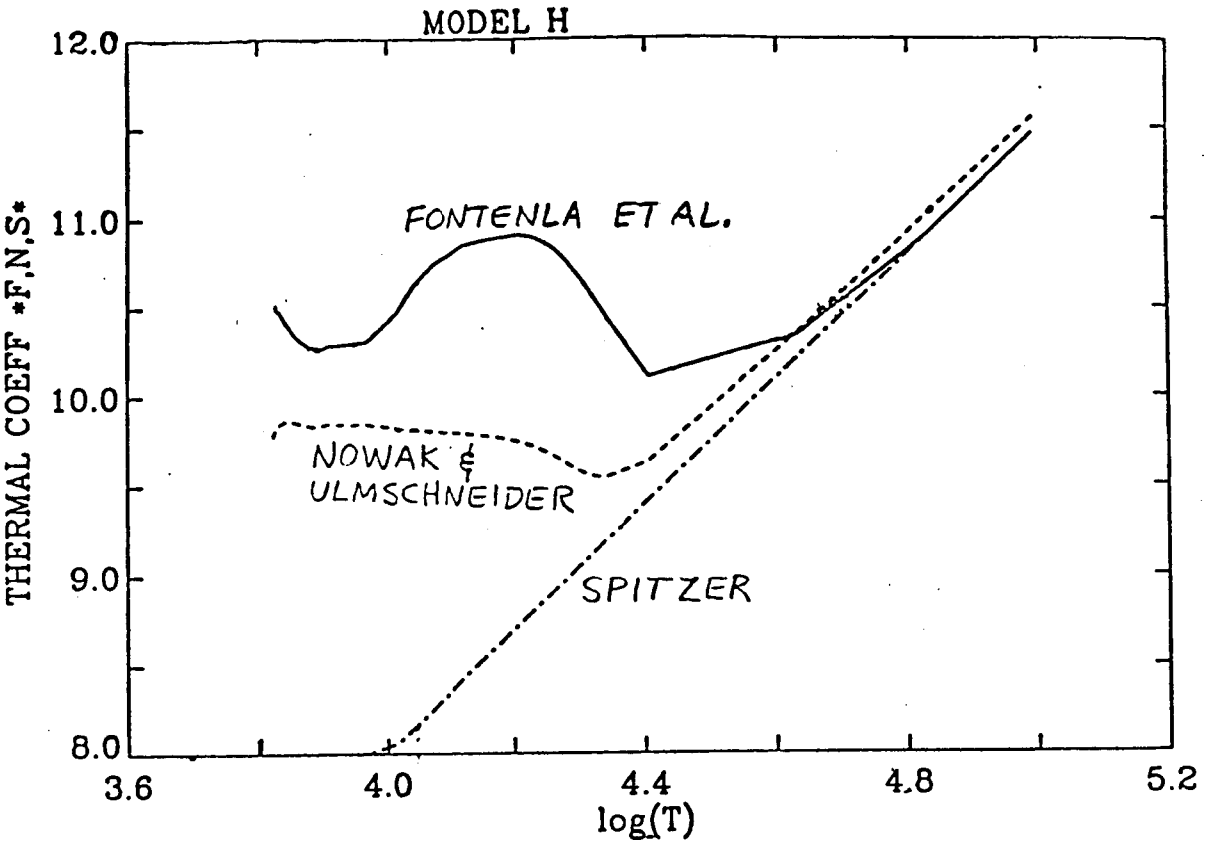
We have carried out energy-balance model atmosphere calculations for the chromosphere and transition region above T = 8000K. The model below this temperature is assumed to be Model C of Vernazza, Avrett and Loeser (1981). Apart from this constraint at the lower boundary, the only adjustable parameter in our calculation is the energy input from the corona at 100000K. The temperature structure between 100000 and 8000 K is calculated resulting from the energy balance between this input, the internal energy transport, and the hydrogen radiative losses. The densities are determined from hydrostatic equilibrium. We carry out the same multi-level, non-LTE calculations with Lyman-alpha partial redistribution as in the earlier model determination.

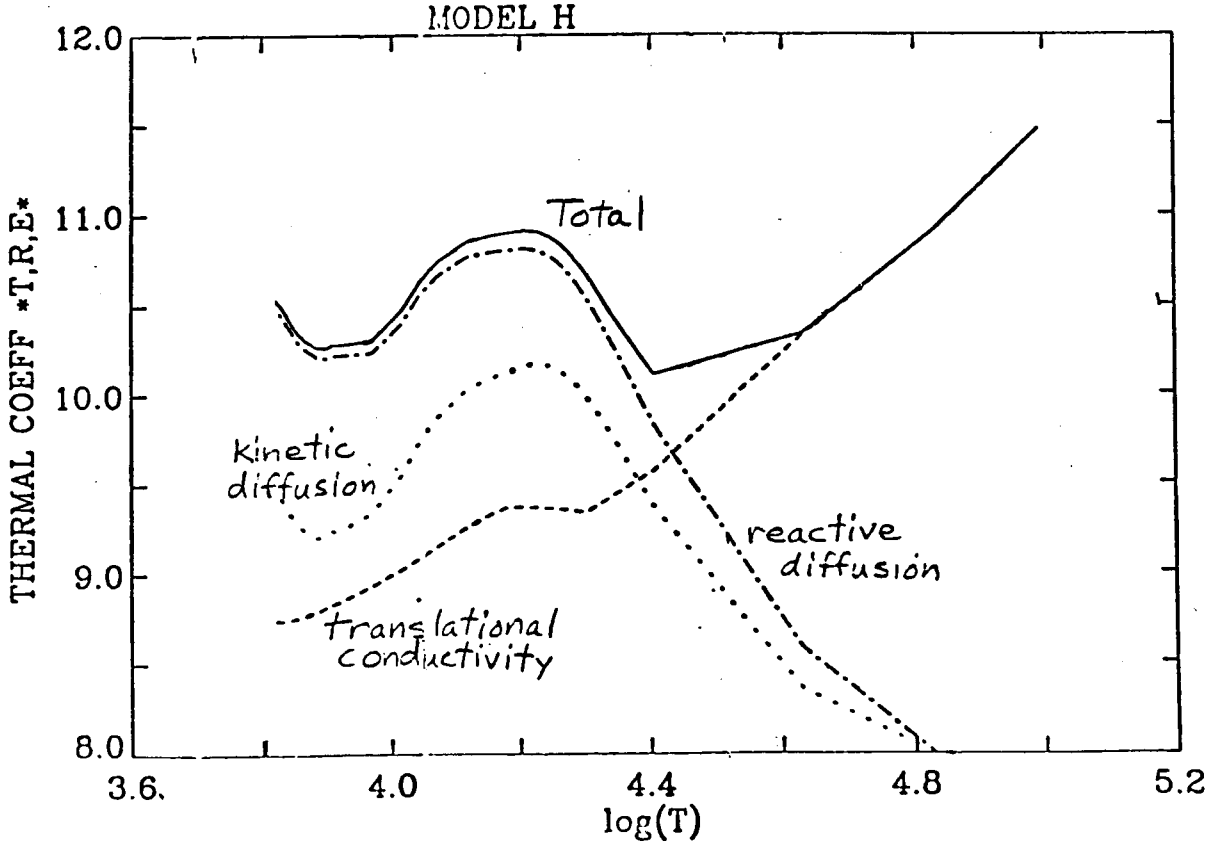
Figure 2 shows the resulting temperature distribution from one of these energy balance calculations, compared with the earlier plateau model. The empirical model could have had a plateau of smaller geometrical extent if the plateau temperature had been lower. The energy-balance model shows that more than half of the integrated Lyman-alpha emission originates at temperatures below 12000K.

We find that the observed profile as well as the integrated intensity of Lyman alpha can be matched approximately by means of the energy-balance calculations. Also the calculated Lyman continum intensity matches with the observed. However, it is not yet clear that our calculated Lyman beta line has the reported absorption reversal at line center. This had been one of the reasons for introducing the empirical plateau.

Our main conclusion is that we can account for the observed Lyman alpha line as a result of an improved theory of conduction and diffusion in the transition region. Details of the theoretical formulation of the transport coefficients are given in papers by Fontenla and by Fontenla, Rovira, and Fontan submitted to the Astrophysical Journal.

We have calculated the first order perturbations to the Maxwellian distributions from the method of Fontenla, finding that there are no difficulties with regard to the heat flux. In the region of the largest temperature gradient, the perturbations to the electron and proton distributions are small (so that the first-order approach is accurate) for $E/kT < 10$. For atoms, the perturbation is small for $E/kT < 6$. Considering the ionization rates, the relevant departure of the electron distribution function from a Maxwellian distribution starts at more than 20 eV, and then the classical formulas for hydrogen ionization hold for the region in which the Lyman alpha line is formed.


MODEL H
12.0
11.0
10.0
9.0
8.0
THERMAL COEFF *F,N,S*
FONTENLA ET AL.
NOWAK & ULMSCHNEIDER
SPITZER
3.6
4.0
4.4
4.8
5.2
log(T)


MODEL H
12.0
11.0
10.0
9.0
8.0
THERMAL COEFF *T,R,E*
Total
kinetic diffusion
reactive diffusion
translational conductivity
3.6
4.0
4.4
4.8
5.2
log(T)

The Model C temperature distribution, from VAL-III.